Applied Soil Ecology 130 (2018) 143–148

Contents lists available at ScienceDirect

Applied Soil Ecology

journal homepage: www.elsevier.com/locate/apsoil

Short communication

Interactive effects of liming and nitrogen management on carbon mineralization in grassland soils

Iris Lochon[a,b], Pascal Carrère[a], Sandrine Revaillot[a], Juliette M.G. Bloor[a,*]

[a] UCA, INRA, VetAgro-Sup, UREP, 63000 Clermont-Ferrand, France
[b] CMI, Roullier Group, 35400 St Malo, France

ARTICLE INFO

Keywords:
Acidic soils
Calcium carbonate
CO_2 emissions
Grassland management
Soil organic matter

ABSTRACT

Grassland management has the potential to modify soil carbon (C) mineralization, but the relative importance of combined soil improvers or fertilizers and land use intensity on C mineralization remains unclear. We used laboratory incubations to examine the interactive effects of lime addition, mineral N inputs and grassland management intensity on soil C mineralization potential over 84 days. Monitoring of CO_2 production and O_2 consumption was coupled with measurements of soil pH and microbial biomass for soils obtained from grasslands with contrasting levels of land management intensity (extensive versus intensive N management) at each of three upland sites. Lime addition increased soil pH, cumulative CO_2 production and O_2 consumption across all N treatments and soils. These positive effects of liming either partly or fully compensated the observed negative effects of N on CO_2 and O_2 fluxes. Responses to combined liming and N addition varied depending on management intensity; N addition had no effect on liming response ratios for O_2 consumption at intensively-managed sites, but increased the magnitude of positive liming response ratios for O_2 consumption at extensively-managed sites. Overall, our results suggest that the magnitude of liming-induced increases in C mineralization is mediated by effects of both past and present N management on the soil microbial community. This highlights the importance of considering agricultural practices when assessing the net contribution of agricultural liming to soil-atmosphere feedbacks on climate change.

1. Introduction

Soil organic carbon (C) mineralization is a key biogeochemical process with the potential to regulate global atmospheric CO_2 concentrations. In agroecosystems, management practices modify both biotic and abiotic soil properties, which may influence the dynamics of soil organic matter. However, the impact of simultaneous management practices on C mineralization in different soils remains unclear. Improved understanding of the drivers of soil C mineralization is critical for the development of sustainable agricultural practices and effective climate mitigation strategies (Lal, 2004; Fornara et al., 2011).

Lime and inorganic nitrogen fertilizers are commonly added to agricultural soils to improve plant productivity (Haynes and Naidu, 1998). In temperate grasslands, the aim of liming is to increase soil pH and offset soil acidity, providing optimum conditions for plant growth and improving plant nutrient-use efficiency. Liming-induced increases in pH generally promote microbial activity, and are often considered to stimulate C mineralization (Curtin et al., 1998; Paradelo et al., 2015), although lime-derived carbon also contributes to CO_2 emissions and may lead to overestimations of soil organic C mineralization from soils (Bertrand et al., 2007; Biasi et al., 2008). Conversely, nitrogen addition typically decreases soil respiration and microbial biomass in grassland soils (Geisseler et al., 2016; Ramirez et al., 2012). In practice, liming and N inputs may both be applied to managed grasslands since N fertilization and NH_4^+ accumulation promote soil acidification (Bolan and Hedley, 2003). Indeed, neutralizing effects of lime may counteract the acidifying effects of N on soil pH and microbial biomass (Kennedy et al., 2004). Moreover, site management history could also influence the net effect of soil improvers on soil C dynamics via changes in the soil microbial community (Grayston et al., 2004; Tardy et al., 2015). For example, extensively-managed sites are characterized by soil with a higher fungal: biomass ratio and slower nutrient turnover compared with intensively-managed sites (De Deyn et al., 2008; Wardle et al., 2004). To date, few studies have investigated the interactions between liming and N inputs on C mineralization, and the influence of management intensity on these interactions remains unknown.

Here we investigate the interactive effects of lime addition, mineral N inputs and management intensity on soil C mineralization potential

* Corresponding author at: INRA-UREP, 5 Chemin de Beaulieu, F-63000 Clermont-Ferrand, France.
E-mail address: juliette.bloor@inra.fr (J.M.G. Bloor).

https://doi.org/10.1016/j.apsoil.2018.06.010
Received 19 January 2018; Received in revised form 2 June 2018; Accepted 12 June 2018
Available online 19 June 2018
0929-1393/ © 2018 Elsevier B.V. All rights reserved.

Table 1
Land use and soil characteristics of study sites (based on analyses carried out immediately prior to the experiment).

Site	Texture	Management Intensity	Soil code	Nitrogen fertilisation (kg N ha^{-1} yr^{-1})	Clay content (%)	Silt content (%)	Organic Matter (%)	Organic C (g kg^{-1} dry soil)	Total N (g kg^{-1} dry soil)	CEC Metson (Cmol + kg^{-1} dry soil)	Water Content at −80 kPa (%)
Laqueuille	Silt Loam	Extensive	L.Ext	0	14.3	60.1	18.3	106.0	10.2	30.8	74.6
		Intensive	L.Int	210	17.4	61.1	20.3	118.0	11.5	32.6	85.6
Blatiere	Sandy clay loam	Extensive	B.Ext	0	22.1	22.4	7.4	42.9	4.2	21.4	50.8
		Intensive	B.Int	240	22.2	24.7	6.9	40.0	3.9	20.5	55.5
Moine	Clay loam	Extensive	M.Ext	0	29.2	28.0	9.0	51.8	5.2	27.0	46.1
		Intensive	M.Int	240	30.4	31.1	9.1	52.5	5.2	29.0	47.7

using a three-month laboratory incubation study. Incubations are a useful tool for comparing soil C mineralization under standardized conditions (Zhou et al., 2012). We hypothesize that lime addition will increase soil O_2 consumption and CO_2 emissions via changes in pH, and test whether N inputs modify the impact of liming on potential C mineralization rates. We also predict that effects of liming and N inputs on potential C mineralization rates are modified by management intensity due to management-induced changes in microbial biomass and/or activity.

2. Material and methods

2.1. Soil sampling

Three upland grassland sites were selected from a long-term grassland management trial in Central France (Theix-Laqueuille, http://www.soere-acbb.com): Laqueuille (L), Blatière (B) and Moine (M). At each site, we selected a pair of grasslands with contrasting levels of management intensity: 0 versus 210–240 kg N ha^{-1} yr^{-1}, 'extensive' (Ext) and 'intensive' (Int) management respectively, giving a total of six experimental soils (Table 1). One soil sample (0–10 cm depth) was taken for each experimental soil in November 2016, and all soil samples were kept for one month at 4 °C prior to analysis. The soil was then homogenized by sieving (2 mm mesh), and pre-incubated for ten days in the dark at 20 °C, at a water potential corresponding to -80 kPa (moisture content from 46.1% to 85.6% on a dry weight basis depending on site).

2.2. Experimental design and incubations

Lime treatments (control, $CaCO_3$) were crossed with N treatments (control, NH_4NO_3) and management intensity (Ext, Int) in order to investigate interactive effects of $CaCO_3$, N fertilization and management. All eight treatment combinations were replicated three times (three independent sites), and soils for each treatment and replicate combination were incubated in quadruplet (or triplicate for one site). This resulted in 92 soil samples for incubation.

All soil samples (15 g dry weight equivalent, adjusted to -80 kPa water potential) were incubated aerobically for 84 days in the dark at 20 °C in 125 ml air-tight glass jars. Lime was mixed into soil at a rate of 4 T ha^{-1} immediately prior to incubation (31.5 mg $CaCO_3$ per jar), whereas N was mixed into soil at a rate of 85 kg ha^{-1} equivalent (2 mg NH_4NO_3 per jar). Both lime and N were added to the soil in powder form (Analytical grade products).

2.3. Measurements during soil incubation

Evolved CO_2 and O_2 consumption were determined at 13 dates during the incubation period (2, 4, 7, 9, 11, 14, 18, 25, 36, 46, 56, 70, 84 days). Values of O_2 consumption were used as an indicator of soil organic carbon mineralization, whereas CO_2 measurements represent total CO_2 emissions from organic and inorganic (lime) sources. At each sampling date, 3 ml of air was taken from each jar and injected into a gas chromatograph (PerkinElmer – Clarus 480). After measuring gas concentrations, all the jars were ventilated with moist CO_2-free air to prevent soil drying. Gas concentrations were corrected for both the volume of air available in each flask and the air pressure on the day of measurement/ventilation. Consumption of O_2 at each date was calculated as the difference between the O_2 concentration of CO_2-free air used for ventilation (20.5%) minus the actual O_2 concentration in sample jars, and expressed as mg O-O_2 kg^{-1} dry soil. Cumulative CO_2 production was calculated as the sum of C-CO_2 evolved at each measurement interval per kg dry soil. During the experiment, the average CO_2 concentration in the flask headspace was 2.65% (standard error = 0.29).

At the end of the incubation period, soils in the jars were sampled in

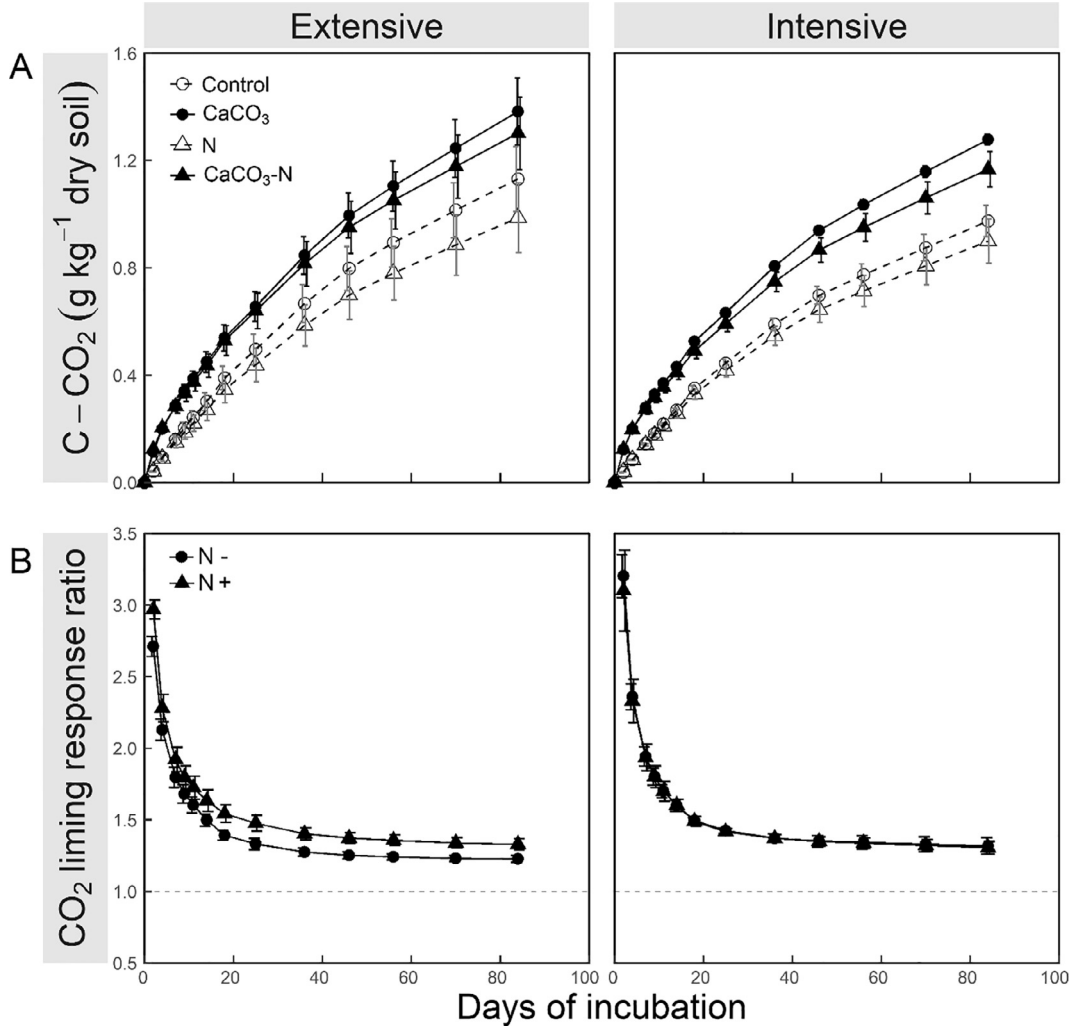

Fig. 1. Effects of interactive $CaCO_3$ and N treatments on the kinetics of (A) cumulative CO_2 emissions and (B) liming response ratios based on CO_2 production for soils subjected to long-term extensive or intensive management practices. Liming response ratios are presented for each soil in the presence or absence of N inputs. Data are means and standard errors (n = 3).

order to measure pH_{H2O} (soil: water ratio of 1:2) and microbial biomass C. Microbial biomass was measured on 5 g subsamples of the soil using the chloroform fumigation-incubation method and extraction with 0.5 M K_2SO_4 solution (Brookes et al., 1985). Additional 5 g soil samples were oven-dried (105 °C, 24 h) to determine soil moisture content.

2.4. Statistical analyses

Experimental treatment and grassland management effects were assessed using three-way, fully-factorial analysis of variance ($CaCO_3$, N and management intensity as fixed main effects, site as a random effect). In order to avoid pseudo-replication, means were taken for each variable measured from the three-four incubation jars per treatment and soil. Analyses were performed on the cumulative amount of CO_2 evolved and the total consumption of O_2 after 84 days of incubation, as well as on pH and microbial biomass using the three mean values for each of the eight treatment combinations.

Liming response ratios in the absence and presence of N inputs were calculated as $CaCO_3$/Control and $CaCO_3$-N/N respectively for variables showing significant responses to $CaCO_3$ addition. Responses to liming were then analysed with two-way analysis of variance (N and management intensity as fixed effects, site as a random effect). Standardized soil responses to treatments were calculated as $CaCO_3$/Control, N/Control and $CaCO_3$-N/Control ratios for pH, total O_2 consumption and microbial biomass data. Analyses were carried out using R software and nlme and ggplot2 packages (R Core Team, 2013).

3. Results

3.1. CO_2 production and O_2 consumption

The cumulative CO_2 produced in control soils ranged from 0.88 to 1.36 g C-CO_2 kg^{-1} dry soil across sites at the end of the incubation period (Fig. 1A). Lime addition had a positive effect on the total CO_2 emitted, irrespective of N treatment and management intensity (+29.5% on average; Fig. 1A, Table S1). The total consumption of O_2 in the control soils ranged from 1.76 to 2.69 g O-O_2 per kg of dry soil across soils at the end of the incubation period (Fig. 2A). As with CO_2 emissions, lime addition had a positive effect on the total O_2 consumed across N treatments and management intensity (+10.3% on average; Fig. 2A, Table S1). In general, N inputs reduced both CO_2 emissions (−10.6% on average; Fig. 1A, Table S1) and O_2 consumption (−6.5% on average; Fig. 2A, Table S1). Increasing management intensity also had a negative effect on CO_2 emissions and O_2 consumption (−11.2% and −12.3% on average in intensive soils for CO_2 and O_2 respectively; Figs. 1A and 2A, Table S1). Neither CO_2 nor O_2 values showed any significant interactions between treatments (Table S1).

Liming response ratios for CO_2 emissions and O_2 consumption

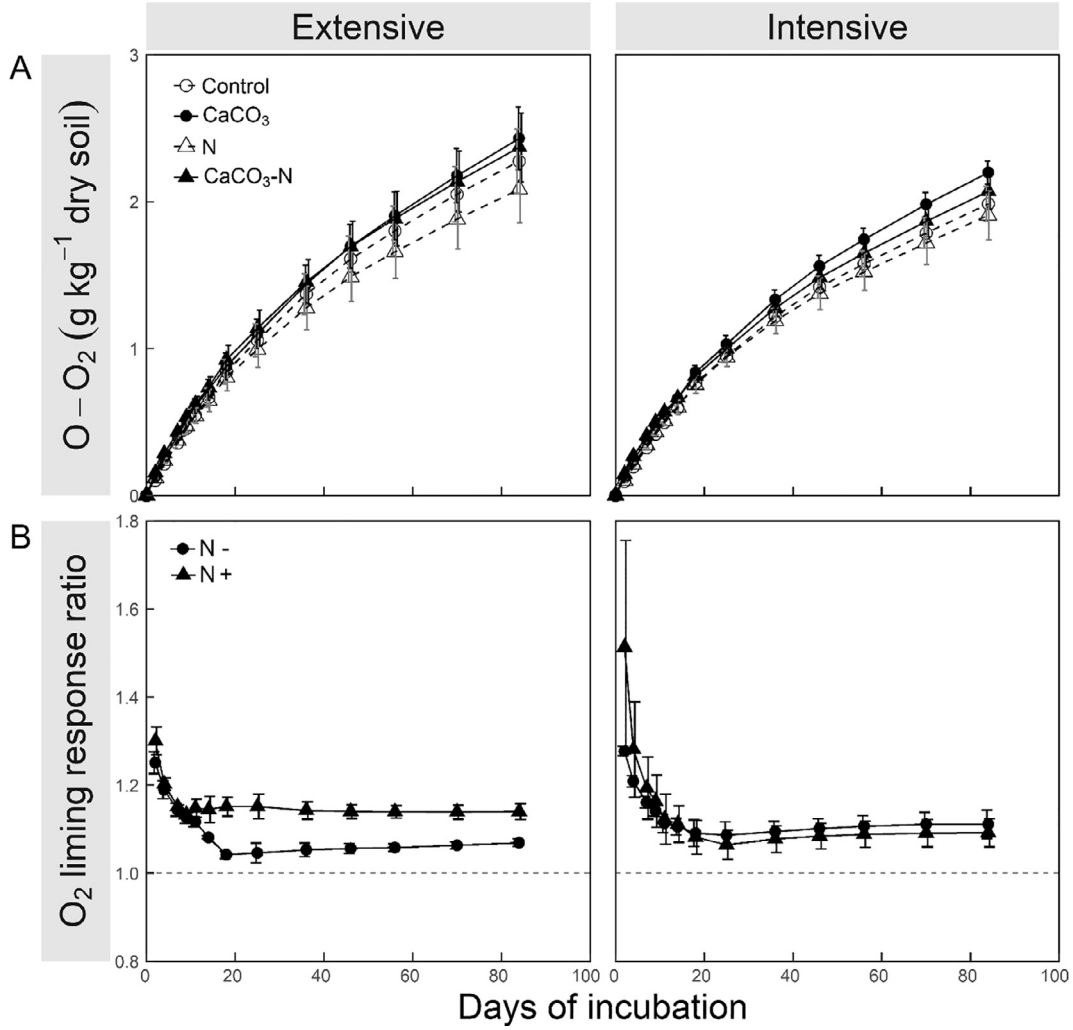

Fig. 2. Effects of interactive $CaCO_3$ and N treatments on the kinetics of (A) O_2 consumption and (B) liming response ratios based on O_2 consumption for soils subjected to long-term extensive or intensive management practices. Liming response ratios are presented for each soil in the presence or absence of N inputs. Data are means and standard errors (n = 3).

showed a significant interaction between N and management intensity (CO_2: $F_{1,6} = 9.22$, $p < 0.05$, O_2: $F_{1,6} = 6.80$, $p < 0.05$). In extensively-managed soils, liming-induced increases in both cumulative CO_2 production and total O_2 consumption were higher when lime was combined with N (CO_2: +10% on average, Fig. 1B; O_2: +7% on average, Fig. 2B). However, liming response ratios for CO_2 emissions and O_2 consumption showed no difference in the presence or absence of N for intensive soils.

3.2. Soil properties at the end of the incubation period

Liming had a consistently positive effect on soil pH recorded after 84 days across treatments (+0.7 pH units on average, Table S1). In contrast, management intensity had a negative effect on soil pH (−0.5 pH units on average in intensive soils, Table S1). Soil pH did not respond to N treatment or show any significant treatment interactions (Table S1). Furthermore, liming response ratios for pH were unaffected by either N or management intensity ($p > 0.05$ in all cases). Microbial biomass C showed a negative response to management intensity (−23.4% for intensive soils compared to extensive soils), but did not respond to liming or N treatments (Table S1).

Overall treatment response ratios based on O_2 fluxes and soil variables recorded after 84 days of incubation provided evidence for treatment differentiation across soils (Fig. 3). Liming (with or without N) was associated with positive changes in pH, microbial biomass C and O_2 consumption, whereas N inputs alone were associated with negative changes in these parameters.

4. Discussion

In line with our predictions, we found that liming increased O_2 consumption (our proxy for C mineralization) in all study soils. These lime-induced increases in C mineralisation were associated with a concurrent increase in soil pH. Increases in pH may modify microbial activity, increase resource availability and microbial C-use efficiency and/or alter microbial community structure (Grover et al., 2017; Kennedy et al., 2004; Rousk et al., 2010). Our results are consistent with pH regulation of microbial processes (Curtin et al. 1998; Kemmitt et al., 2006), and suggest that liming may accelerate soil organic matter turnover rates (Adams and Adams, 1983; Paradelo et al., 2015).

Broad-scale soil studies have shown that nitrogen addition generally reduces microbial biomass and C mineralization via shifts in microbial community structure and enzyme activities (Ramirez et al., 2012). Based on previous results of combined N and $CaCO_3$ inputs on microbial biomass (Kennedy et al. 2004), we expected that positive effects of liming would buffer the negative effects of N on C mineralization either partly or completely. This was consistently the case across our study sites (as highlighted by the Fig. 3 representing standardised treatment

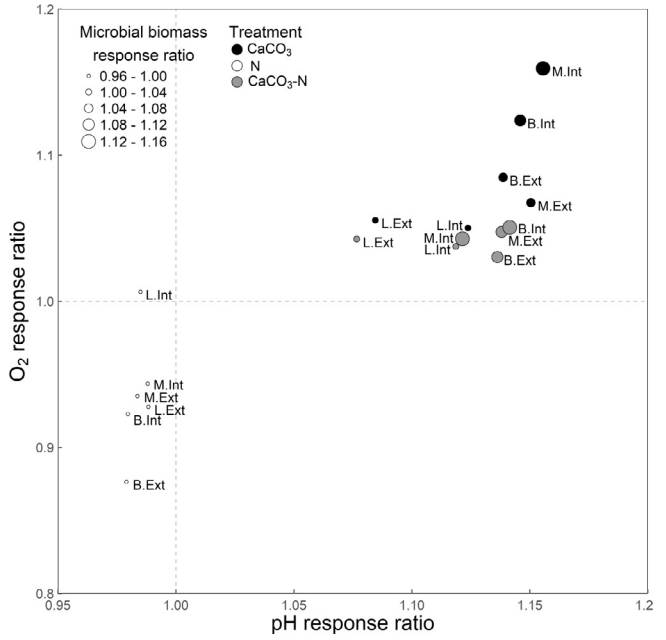

Fig. 3. Treatment response ratios for total O_2 consumption, soil pH and microbial biomass C after 84 days of incubation for grassland soils subjected to long-term extensive or intensive management practices. All treatment response ratios are calculated relative to the control.

responses for all soils). However, the liming responses observed for C mineralization (O_2 consumption) varied depending on both N addition and historical management intensity. Unlike intensively-managed sites where liming response ratios were equally high in the presence or absence of N inputs, liming response ratios for O_2 consumption were of greater magnitude at extensively-managed sites when lime was combined with N. Moreover, the liming responses for O_2 consumption at extensively-managed sites with N inputs were close to those observed for intensively-managed sites.

Interactive effects of N fertilisation and management intensity in the present study suggest a lower sensitivity to lime in extensively-managed sites in the absence of N, likely due to differences in both microbial abundances and microbial community structure. Extensively-managed systems commonly have fungi-dominated soil communities with slow process rates (Grayston et al., 2004; Grigulis et al., 2013), and soil fungi are known to show high resistance to changes in environmental conditions (de Vries and Shade, 2013; Rousk et al., 2010). It seems reasonable to expect that lime-induced increases in soil pH promoted the abundance of soil bacterial groups for our extensive sites (Rousk et al., 2009). Shifts towards fast-growing bacteria, better able to process mineral N, could therefore explain the increase in gas fluxes observed in the $CaCO_3$-N treatment for extensive sites. In the intensive sites, the absence of liming response differences may reflect the presence of bacterial-dominated soil communities pre-adapted to high N inputs.

Overall, our results suggest that effects of both present and past N management on the soil microbial community mediate the magnitude of liming-induced increases in C mineralization. Unsurprisingly, liming responses of CO_2 production mirrored those of C mineralization (O_2 consumption), although the magnitude of interactive effects was generally greater for CO_2 production. These findings underline the need to consider N inputs and historical management intensity when assessing lime-induced benefits (pH improvement, potential reduction of N losses; Holland et al., 2018) against lime-induced CO_2 emissions for agricultural recommendations (Goulding, 2016; Kunhikrishnan et al., 2016). Current CO_2 budget calculations consider lime-induced emissions of CO_2 as a fixed factor, and may therefore contribute to inaccuracies in estimates of the global warming potential of agricultural practices (Fornara et al., 2011). Of course, the generality of our findings should be tested for a broader range of soil types and climatic conditions. Future studies should also examine the contribution of different microbial groups to better understand the interactions between soil responses to liming and N management practices, both past and present.

Acknowledgements

The authors thank Sébastien Fontaine for assistance with experimental design. This study was supported by a CIFRE doctoral fellowship to IL.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apsoil.2018.06.010.

References

Adams, T.M., Adams, S.N., 1983. The effects of liming and soil pH on carbon and nitrogen contained in the soil biomass. J. Agric. Sci. 101, 553.

Bertrand, I., Delfosse, O., Mary, B., 2007. Carbon and nitrogen mineralization in acidic, limed and calcareous agricultural soils: apparent and actual effects. Soil Biol. Biochem. 39, 276–288.

Biasi, C., Lind, S.E., Pekkarinen, N.M., Huttunen, J.T., Shurpali, N.J., Hyvönen, N.P., Repo, M.E., Martikainen, P.J., 2008. Direct experimental evidence for the contribution of lime to CO2 release from managed peat soil. Soil Biol. Biochem. 40, 2660–2669.

Bolan, N.S., Hedley, M.J., 2003. Role of carbon, nitrogen, and sulfur cycles in soil acidification. In: Rengek, Z. (Ed.), Handbook of Soil Acidity. Marcel Dekker, New York, pp. 29–56.

Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17, 837–842.

Curtin, D., Campbell, C.A., Jalil, A., 1998. Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. Soil Biol. Biochem. 30, 57–64.

De Deyn, G.B., Cornelissen, J.H.C., Bardgett, R.D., 2008. Plant functional traits and soil carbon sequestration in contrasting biomes. Ecol. Lett. 11, 516–531.

de Vries, F.T., Shade, A., 2013. Controls on soil microbial community stability under climate change. Front. Microbiol. 4, 265.

Fornara, D.A., Steinbeiss, S., McNamara, N.P., Gleixner, G., Oakley, S., Poulton, P.R., Macdonald, A.J., Bardgett, R.D., 2011. Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland. Global Change Biol. 17, 1925–1934. http://dx.doi.org/10.1111/j.1365-2486.2010.02328.x.

Geisseler, D., Lazicki, P.A., Scow, K.M., 2016. Mineral nitrogen input decreases microbial biomass in soils under grasslands but not annual crops. Appl. Soil Ecol. 106, 1–10.

Goulding, K.W.T., 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use Manage. 32, 390–399.

Grayston, S., Campbell, C., Bardgett, R., Mawdsley, J., Clegg, C., Ritz, K., Griffiths, B., Rodwell, J., Edwards, S., Davies, W., Elston, D., Millard, P., 2004. Assessing shifts in microbial community structure across a range of grasslands of differing management intensity using CLPP, PLFA and community DNA techniques. Appl. Soil Ecol. 25, 63–84.

Grigulis, K., Lavorel, S., Krainer, U., Legay, N., Baxendale, C., Dumont, M., Kastl, E., Arnoldi, C., Bardgett, R.D., Poly, F., Pommier, T., Schloter, M., Tappeiner, U., Bahn, M., Clément, J.-C., 2013. Relative contributions of plant traits and soil microbial properties to mountain grassland ecosystem services. J. Ecol. 101, 47–57.

Grover, S.P., Butterly, C.R., Wang, X., Tang, C., 2017. The short-term effects of liming on organic carbon mineralisation in two acidic soils as affected by different rates and application depths of lime. Biol. Fertil. Soils 53, 431–443.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosyst. 51, 123–137.

Holland, J.E., Bennett, A.E., Newton, A.C., White, P.J., McKenzie, B.M., George, T.S., Pakeman, R.J., Bailey, J.S., Fornara, D.A., Hayes, R.C., 2018. Liming impacts on soils, crops and biodiversity in the UK: a review. Sci. Total Environ. 610–611, 316–332.

Kemmitt, S., Wright, D., Goulding, K., Jones, D., 2006. pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil Biol. Biochem. 38, 898–911.

Kennedy, N., Connolly, J., Clipson, N., 2004. Impact of lime, nitrogen and plant species on bacterial community structure in grassland microcosms. Environ. Microbiol. 7, 780–788.

Kunhikrishnan, A., Thangarajan, R., Bolan, N.S., Xu, Y., Mandal, S., Gleeson, D.B., Seshadri, B., Zaman, M., Barton, L., Tang, C., Luo, J., Dalal, R., Ding, W., Kirkham, M. B., Naidu, R., 2016. Functional Relationships of Soil Acidification, Liming, and Greenhouse Gas Flux. 1–71.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Paradelo, R., Virto, I., Chenu, C., 2015. Net effect of liming on soil organic carbon stocks: a review. Agric. Ecosyst. Environ. 202, 98–107.

R Core Team, 2013. R: A language and Environment for Statistical Computing.

Ramirez, K.S., Craine, J.M., Fierer, N., 2012. Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. Global Change Biol. 18, 1918–1927.

Rousk, J., Bååth, E., Brookes, P.C., Lauber, C.L., Lozupone, C., Caporaso, J.G., Knight, R., Fierer, N., 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. ISME J. 4, 1340–1351. http://dx.doi.org/10.1038/ismej.2010.58.

Rousk, J., Brookes, P.C., Bååth, E., 2009. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. Appl. Environ. Microbiol. 75, 1589–1596.

Tardy, V., Spor, A., Mathieu, O., Lévèque, J., Terrat, S., Plassart, P., Regnier, T., Bardgett, R.D., van der Putten, W.H., Roggero, P.P., Seddaiu, G., Bagella, S., Lemanceau, P., Ranjard, L., Maron, P.-A., 2015. Shifts in microbial diversity through land use intensity as drivers of carbon mineralization in soil. Soil Biol. Biochem. 90, 204–213.

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setälä, H., van der Putten, W.H., Wall, D.H., 2004. Ecological linkages between aboveground and belowground biota. Science 304, 1629–1633.

Zhou, X., Chen, C., Wang, Y., Xu, Z., Hu, Z., Cui, X., Hao, Y., 2012. Effects of warming and increased precipitation on soil carbon mineralization in an Inner Mongolian grassland after 6 years of treatments. Biol. Fertil. Soils 48, 859–866.